CDF note 9071

Search for Neutral MSSM Higgs Bosons Decaying to Tau Pairs with 1.8 fb^{-1} of Data

The CDF Collaboration
URL http://www-cdf.fnal.gov
(Dated: October 22, 2007)

We present the results of a search for inclusive production of neutral MSSM Higgs bosons in $p\bar{p}$ collisions at 1.96 TeV center of mass energy. The data were collected with the CDF II detector at the Tevatron collider at Fermilab, and correspond to an integrated luminosity of 1.8 fb^{-1}. The search is performed in the di-τ Higgs decay mode. No significant excess of events above the standard model backgrounds is observed. The measurements are used to set exclusion limits on production cross-section times branching fraction to tau pairs for Higgs masses in the range from 90 to 250 GeV/c^2.

Preliminary Results for Fall 2007 Presentations

I. INTRODUCTION

One of the outstanding questions in modern particle physics is the dynamics of electroweak (EW) symmetry breaking and the origin of particle masses. In the standard model (SM), EW symmetry is spontaneously broken through the Higgs mechanism [1], by the introduction of a doublet of self-interacting complex scalar fields with non-zero vacuum expectation values. The physical manifestation of this scenario is the existence of a massive scalar Higgs boson h_{SM}. Theoretical difficulties related to divergent radiative corrections to the h_{SM} mass have natural solution in supersymmetric (SUSY) models.

The minimal supersymmetric extension of the standard model (MSSM) is the simplest realistic SUSY theory. It requires two Higgs doublets resulting in a Higgs sector with two charged and three neutral scalar bosons. Assuming CP-invariance, one of the neutral bosons (A) is CP-odd, and the other two (h,H) are CP-even. Throughout this Note we use h (H) for the lighter (heavier) CP-even neutral Higgs boson, and ϕ to denote any of h,H,A. At tree level, the MSSM Higgs bosons are described by two free parameters, chosen to be the mass of A (m_A), and $\tan\beta = v_2/v_1$, where v_2, v_1 are the vacuum expectation values of the neutral Higgs fields that couple to up-type and down-type fermions, respectively. The Yukawa couplings of A to down-type fermions (such as the b quark and τ) are enhanced by a factor of $\tan\beta$ relative to the SM. For large $\tan\beta$ one of the CP-even bosons is nearly mass-degenerate with A and has similar couplings.

There are two dominant production mechanisms of neutral MSSM Higgs bosons at hadronic colliders: gluon fusion [2] and $b\bar{b}$ fusion [3, 4]. The leading decay modes of A and the corresponding mass-degenerate CP-even Higgs boson are $\phi \to b\bar{b}$ ($\sim 90\%$) and $\phi \to \tau\tau$ ($\sim 10\%$). Despite the smaller branching fractions, Higgs searches in the di-τ channel have advantages. They do not suffer from the large di-jet and multi-jet backgrounds as $\phi \to b\bar{b}$.

The LEP experiments have excluded $m_A \lesssim 93$ GeV/c^2, and higher-mass A for small $\tan\beta$ [5]. Searches at hadron colliders are complementary, providing sensitivity in the large $\tan\beta$ region. Searches in Run II of the Tevatron by the CDF and DØ collaborations for $\phi \to b\bar{b}$ [6, 7] and $\phi \to \tau\tau$ [8–10] have excluded substantial regions of the MSSM parameter space.

In this Note we present the results of a search for inclusive production of neutral MSSM Higgs bosons in $p\bar{p}$ collisions at $\sqrt{s}$=1.96 TeV. The search is performed in the $\phi \to \tau\tau$ decay channel and uses data collected with the CDF detector in Run II of the Fermilab Tevatron. We detect the tau pairs in three final states: $\tau_e\tau_{had}$, $\tau_\mu\tau_{had}$, and $\tau_e\tau_\mu$, where τ_e, τ_μ, and τ_{had} are short-hand notations for the decay modes $\tau \to e\nu_e\nu_\tau$, $\tau \to \mu\nu_\mu\nu_\tau$, and $\tau \to hadrons\ \nu_\tau$, respectively. The analyzed data sample corresponds to an integrated luminosity of 1.8 fb^{-1}.

II. THE CDF DETECTOR

CDF II is a general purpose detector built to study particles produced in $p\bar{p}$ collisions at $\sqrt{s}$=1.96 TeV. The following is a short overview of the systems relevant to this search.

The CDF II tracking system consists of a cylindrical wire drift chamber and silicon micro-strip detectors, coaxial with the p and $\bar{p}$ beams. It is immersed in a 1.4 T uniform magnetic field produced by a superconducting solenoid. Electromagnetic (EM) and hadronic (HAD) sampling calorimeters are located outside the tracking system and cover pseudorapidity $|\eta| < 3.6$. They are divided into towers with projective geometry. A Shower Maximum Detector (CES) is embedded in the EM calorimeter at a depth of six radiation lengths. CES consists of proportional chambers with anode wires going parallel to the beam axis, and orthogonal cathode strips. CES is used to determine the position of electromagnetic showers with spatial resolution of ~ 0.5 cm. Muons are identified by a system of drift chambers located outside the calorimeter volume. The combined coverage of the central muon detectors extends to $|\eta| < 1.1$. The luminosity is measured by gas Cherenkov counters located in the detector far forward and backward regions ($3.7 < |\eta| < 4.7$) with 6% precision [11]. Detailed description of CDF II can be found in [12].

III. DATA SAMPLE & EVENT SELECTION

The events for the $\tau_e\tau_{had}$ and $\tau_\mu\tau_{had}$ detection modes were selected with "lepton plus track" triggers [13]. They require a lepton (e, μ) candidate and an isolated track with transverse momentum $p_T > 5$ GeV/c, both pointing to the central detector ($|\eta| \lesssim 1$) and having azimuthal separation $\Delta\varphi > 10°$. At trigger level, an electron is defined as a track with $p_T > 8$ GeV/c matched to a cluster in CES, and a cluster in the EM calorimeter with transverse energy $E_T > 8$ GeV. Tracks with $p_T > 8$ GeV/c associated with hits in the muon detectors are identified as muon candidates. The overall trigger efficiency for signal selection is greater than 90%. The evens for the $\tau_e\tau_\mu$ channel are selected with a di-lepton trigger requiring one electron candidate ($E_T > 4$ GeV) and one muon candidate ($p_T > 4$ GeV) in the central detector.

The detection of $\phi \to \tau\tau$ requires identification of e, μ (from leptonic τ decays) and the reconstruction of the products of semi-hadronically decaying τ's. The algorithms for e and μ identification are described in detail in [12]. The electrons and muons are required to be isolated: the scalar sum of the transverse momenta of tracks I_{iso}^{trk} in an isolation cone $\Delta R = \sqrt{(\Delta\phi^2 + \Delta\eta^2)} = 0.4$ should satisfy $I_{iso}^{trk} < 2$ GeV. Additional isolation requirement is applied to electrons and muons for the final states with a hadronically decaying tau based on energy deposited in the calorimeter. The transverse energy I_{iso}^{cal} in a cone of $\Delta R < 0.4$ (excluding E_T deposited by the leptons) should be smaller than the maximum of 2 GeV and $0.1 \times p_T^{e,\mu}$.

The sum of the transverse momenta of the neutrinos from τ decays appears as missing transverse energy ($\not\!\!E_T$). It is determined from the imbalance of energy deposition in the calorimeter in the transverse plane. $\not\!\!E_T$ is corrected for the position of the interaction vertex and transverse momenta of identified muons.

The acceptances for signal and most of the backgrounds are determined from samples of Monte Carlo (MC) simulated events produced by the PYTHIA event generator [14] with CTEQ5L [15] parton distribution functions (PDF's). Tau decays are simulated by the TAUOLA package [16]. Detector response is simulated with a GEANT-based [17] model of the detector.

A. Tau Reconstruction and Isolation

The decay products in τ_{had} appear as narrow jets with low track and π^0 multiplicity. We use a variable-size cone algorithm to associate these particles with τ candidates. The positions of π^0's are determined from hits in the CES detector, and the energy is measured by the EM calorimeter. A charged track with $p_T > 6.0$ GeV/c pointing to a cluster of six or less contiguous towers serves as a "seed" for a tau candidate. The direction of the seed track defines the axis of a signal cone and an isolation annulus. The angular size of the signal cone α_{sig} is a function of the calorimeter cluster energy E_{cl}. The isolation annulus extends from α_{sig} to $\alpha_{iso} = 30^\circ$. The value of α_{sig} is the minimum of 10° and (5 GeV)$/E_{cl}$ rad. To prevent position resolution effects, the minimum value of α_{sig} is set to 0.05 rad for tracks, and 0.1 rad for π^0's. The four-momentum of τ_{had} is calculated from tracks and π^0's contained in the signal cone. Particles in the isolation annulus are used to impose isolation requirements that discriminate against quark and gluon jets: The sum of the transverse momenta of tracks (sum of transverse energy of π^0's) in the isolation annulus is required to be less than 2 GeV/c (1 GeV). The number of tracks with $p_T > 1$ GeV/c in the signal cone (N_{sig}^{trk}) is restricted to one or three (consistent with the dominant τ decay modes). We accept 1-prong (3-prong) tau candidates with transverse momentum of the hadronic system $p_T^{had} > 15$ GeV/c (20 GeV/c), and invariant mass $m_{had} < 1.8$ GeV/c^2. In the $N_{sig}^{trk} = 3$ case the sum of the electric charges must be equal to ± 1. Electrons are rejected by imposing the condition $(E_{cl}/P_{sig}^{trk})(0.95 - f) > 0.1$, f is the fraction of electromagnetic energy in the cluster, and P_{sig}^{trk} is the scalar sum of track momenta in the signal cone. Additionally, we reject 1-prong τ_{had} candidates if they are consistent with an e+brem.

B. Backgrounds

The dominant (and irreducible)background in the final sample of selected events is from Z/γ^* production with subsequent decays to τ pairs. It is estimated using MC simulated events with normalization corresponding to $\sigma(p\bar{p} \to Z/\gamma^*) \times BR(Z/\gamma^* \to ll) = 254.9$ pb in the di-lepton mass region $66 < m_{ll} < 116$ GeV/c^2 [18]. The second-largest contribution is from backgrounds involving gluon or quark jets misidentified as τ_{had}, such as di-jet and multi-jet events, W produced in association with jets, and photon plus jet production. The jet backgrounds in the $\tau_e\tau_\mu$ channel are estimated using events in the isolation sidebands of the leptons. The corresponding backgrounds in the $\tau_e\tau_{had}$ and $\tau_\mu\tau_{had}$ channels are determined by weighting data events containing loosely identified τ_{had} by $jet \to \tau_{had}$ misidentification probabilities ("fake rates"). The fake rates are obtained from independent jet samples, and a parameterized in terms of energy, η position in the calorimeter, and track multiplicity. The third group of considered backgrounds includes Z ($Z \to ee, \mu\mu$), WW, WZ, ZZ, $W\gamma$, $Z\gamma$, and $t\bar{t}$ production. They are determined from MC samples.

C. Event Cuts

The events in the $\tau_e \tau_{had}$ ($\tau_\mu \tau_{had}$) channel are selected by requiring one e (μ) candidate with $p_T^{e(\mu)} > 10$ GeV/c, and one hadronically decaying τ candidate and opposite electric charge. Low-energy multi-jet backgrounds are suppressed by applying a requirements on $H_T = |p_T^{e(\mu)}| + |p_T^{had}| + |\not\!\!E_T|$. For events with a 3-prong tau candidate we require $H_T > 55$ GeV. The $jet \to \tau$ misidentification rate for 1-prong taus is lower and we relax the H_T cuts to $H_T > 50$ (45) GeV for $\tau_e \tau_{had}$ ($\tau_\mu \tau_{had}$).

Events in the $\tau_e \tau_\mu$ channel are selected by requiring one central electron and one central muon satisfying $min(E_T^e, p_T^\mu) > 6$ GeV, $max(E_T^e, p_T^\mu) > 10$ GeV, and $|E_T^e| + |p_T^\mu| > 30$ GeV.

Backgrounds from W + jet events (with $W \to e(\mu)\nu$ and misidentified jet) are suppressed by imposing requirement on the relative directions of the visible tau decay products, and $\not\!\!E_T$. We define a bisection axis ζ of the angle between the directions of τ_1 and τ_2 in the transverse plane. The projections $p_\zeta^{vis} = (\overrightarrow{p}_1^{vis} + \overrightarrow{p}_2^{vis}) \cdot \hat{\zeta}$ and $p_\zeta^{\not E_T} = \overrightarrow{\not\!\!E}_T \cdot \hat{\zeta}$ are required to satisfy $p_\zeta^{\not E_T} > 0.6 p_\zeta^{vis} - 10$ GeV/c. This condition removes $\sim 85\%$ of the surviving W + jet events, while signal losses are $< 5\%$. To suppress backgrounds from $Z \to \mu\mu$ decays we do not accept events with invariant mass of a μ and a single-track τ_{had} candidate within 10 GeV/c^2 of the Z mass if the associated cluster energy of the track is smaller than 10 GeV or $0.4 \times p^{trk}$.

The number of expected SM background events and the number of observed events in the data after applying all selection criteria are summarized in Table I.

source	$\tau_e \tau_{had}$	$\tau_\mu \tau_{had}$	$\tau_e \tau_\mu$
$Z \to \tau\tau$	1376.9 $\pm$ 8.3	1353.7 $\pm$ 8.1	604.8 $\pm$ 5.5
$Z \to ee, \mu\mu$	69.7 $\pm$ 2.0	107.3 $\pm$ 2.3	19.2 $\pm$ 0.9
di-boson events	4.3 $\pm$ 0.1	3.3 $\pm$ 0.05	11.4 $\pm$ 0.1
$t\bar{t}$	3.7 $\pm$ 0.1	3.0 $\pm$ 0.07	9.1 $\pm$ 0.1
jet fakes	466.5 $^{(*)}$	283.6 $^{(*)}$	57.3 $\pm$ 3.3
Sum BG	1921.1	1750.8	701.9
DATA	1979	1666	726

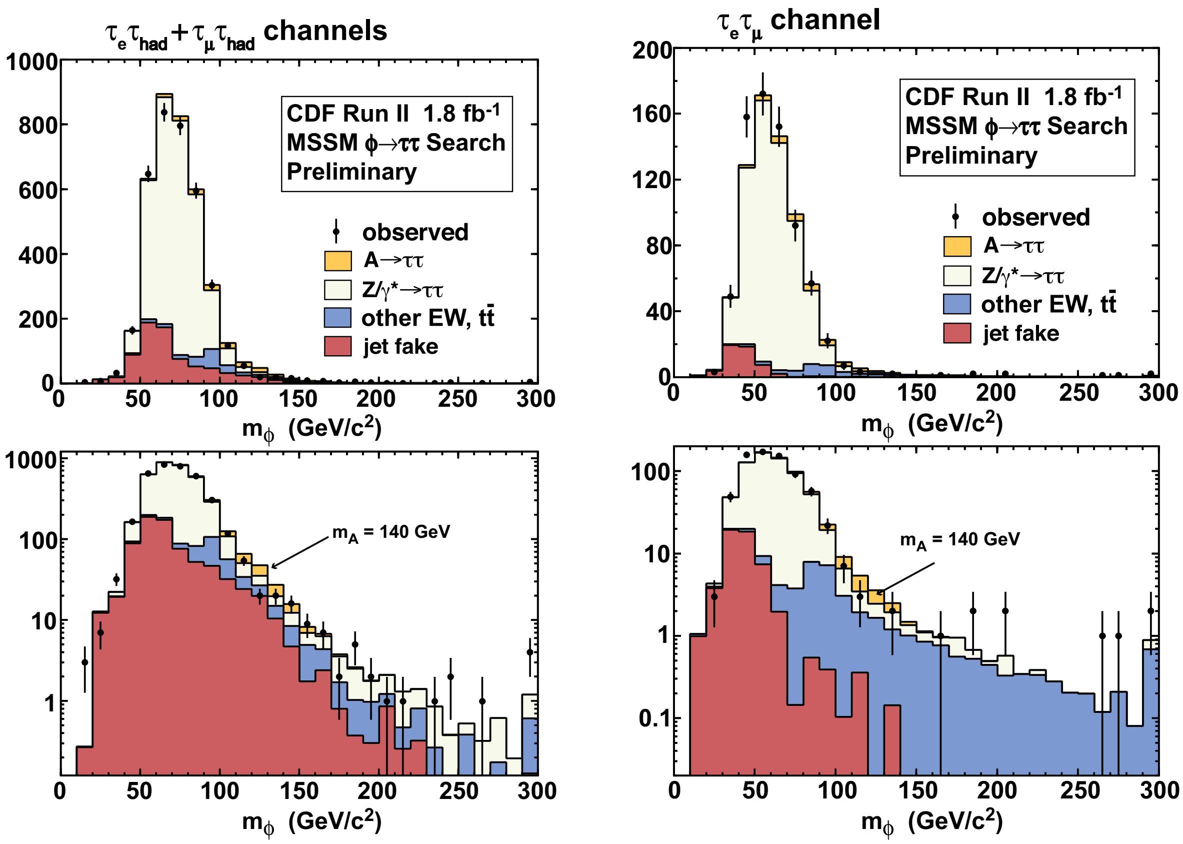
TABLE I: *Predicted backgrounds and observed events in the $\tau_e \tau_{had}$, $\tau_\mu \tau_{had}$, and $\tau_e \tau_\mu$ channels after applying all selection cuts. The quoted errors are statistical only.* $^{(*)}$ *uncertainty is included in systematic.*

The combined signal detection efficiency from the three channels (including trigger efficiency and the tau branching fractions) for a Higgs boson of mass 90 GeV/c^2 (250 GeV/c^2) is 1.0% (3.1%).

D. Systematic Uncertainties

We consider two groups of systematic uncertainties. The first one includes rate uncertainties that affect the expected number of events: the systematic uncertainties for particle identification efficiency are 2.4% (e), 2.6% (μ), and 3.0% (τ_{had}),; the uncertainties in trigger efficiency for the electron, muon, and tau are 0.3% and 1.0%, and 3.0%, respectively; the uncertainty in the determination of backgrounds due to jet misidentification are 20% (15%) for $\tau_e \tau_\mu$ ($\tau_{e/\mu} \tau_{had}$); the imprecise knowledge of the PDF's introduces 5.7% uncertainty on signal acceptance; the uncertainty on the integrated luminosity measurement is 6%.

The second group of uncertainties affects the shape of the distribution used for signal extraction. We consider uncertainties in the data/MC energy scales of e and τ_{had} (1%), and the effect of jet energy scale [19] on the determination of missing transverse energy.



(a) $\tau_e\tau_{had}$ and $\tau_\mu\tau_{had}$ channels combined

(b) $\tau_e\tau_\mu$ channel

FIG. 1: Partially reconstructed di-tau mass. The normalization of the backgrounds and signal (m_A=140 GeV/c^2) correspond to the fit results for signal exclusion at 95% CL.

IV. RESULTS

To probe for possible Higgs signal we perform binned likelihood fits of the partially reconstructed mass of the di-τ system (m_{vis}) defined as the invariant mass of the visible tau decay products and $\not{E}_T$. In the fits, the backgrounds are allowed to float within limits set by Gaussian constraints corresponding to the systematic uncertainties in trigger efficiencies, particle identification, production cross sections, PDF's, event cuts, and luminosity measurement.

Potential differences in m_{vis} shapes between data and the MC simulation in different channels are treated as systematic uncertainties using a "template morphing" technique. We create signal and background m_{vis} templates with nominal MC energy scales, and energy scales shifted according to the uncertainties in the electron, tau, and jet energies. In calculating the expected number of events in a bin, we allow a morphing parameter to control the admixture of the nominal and shifted bin efficiency.

An example fit for $m_A = 140$ GeV$/c^2$ is shown in Figure IV. The normalization of the backgrounds and signal corresponds to the fit results for 95% CL signal exclusion.

We observe no signal evidence for $m_A = 90 - 250$ GeV$/c^2$, and set exclusion limits at 95% CL on $\sigma(p\bar{p} \to \phi + X) \times BR(\phi \to \tau\tau)$ as shown in Figure 2. The sensitivity of the limit-setting procedure is determined from MC simulations assuming no signal. The results are shown on Figure 2 as "expected limits".

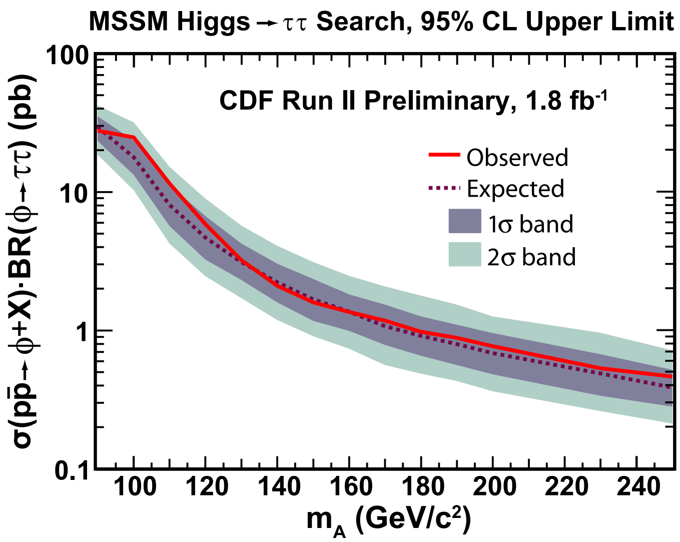


FIG. 2: Observed and expected limits at 95% CL for Higgs production cross-section times branching fraction to τ pairs.

V. INTERPRETATION OF THE RESULTS IN MSSM

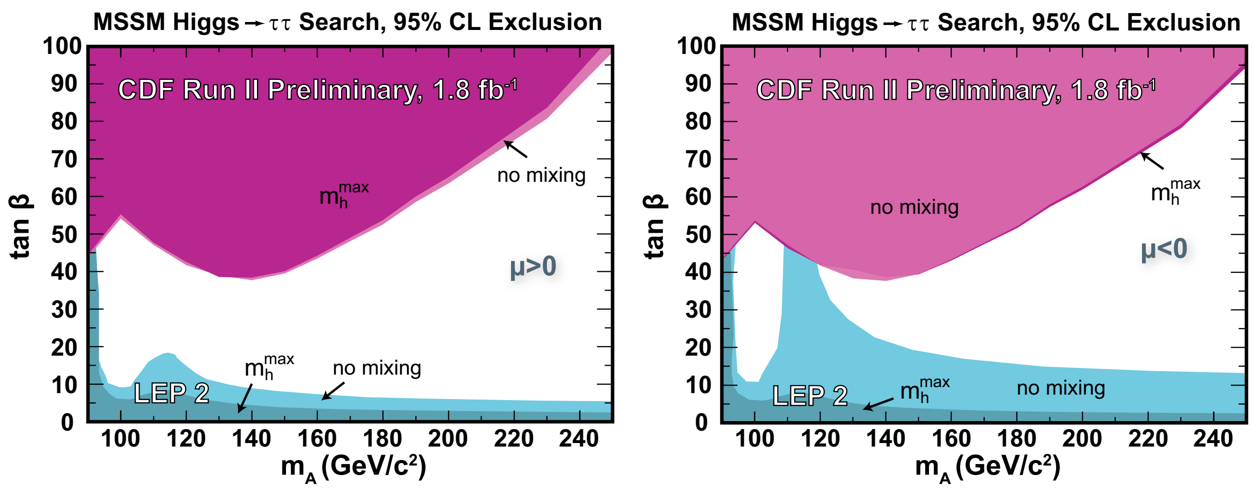
Using the theoretical predictions for the MSSM Higgs production and decay to τ pairs we interpret the limits on $\sigma(p\bar{p} \to \phi + X) \times BR(\phi \to \tau\tau)$ as exclusions of parameter regions in the $\tan\beta$ *vs* m_A plane. The cross sections are obtained from SM calculations and scaling factors $\sigma_{MSSM}/\sigma_{SM}$ accounting for the modified Higgs couplings [20]. The cross sections for gluon fusion mediated by a b-quark loop are calculated with the HIGLU program [21]. The corresponding values for $b\bar{b} \to \phi + X$ are taken from [4]. The scaling factors and $BR(\phi \to \tau\tau)$ are calculated with the FeynHiggs program [22]. They depend on m_A, $\tan\beta$, the $SU(2)$ gaugino mass parameter M_2, the SUSY mass scale M_{SUSY}, the squark mixing parameter X_t, the gluino mass $m_{\tilde{g}}$, and the Higgs mixing parameter μ. We consider four benchmarks [23]: the m_h^{max} and no-mixing scenarios, with $\mu = -200$ Gev and $\mu = +200$ GeV. The excluded $\tan\beta$ regions as a function of m_A are shown in Figure 3.

VI. CONCLUSION

The di-τ decay channel is a powerful search mode for neutral MSSM Higgs bosons produced in $p\bar{p}$ collisions. The expected reach of the presented search extends below $\tan\beta = 40$ for $m_A = 120 - 160$ GeV/c^2. We expect to achieve significant improvement in sensitivity with improved signal extraction techniques.

Acknowledgments

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; the Bundesministerium für Bildung und Forschung, Germany; the Korean Science and Engineering Foundation and the Korean Research Foundation; the Particle Physics and Astronomy Research Council and the Royal Society, UK; the Russian Foundation for Basic Research; the Comisión Interministerial de Ciencia y Tecnología, Spain; in part by the European Community's Human Potential Programme



(a) $\mu > 0$ (b) $\mu < 0$

FIG. 3: Excluded region in $\tan\beta$ *vs* m_A plane for the m_h^{max} and no-mixing scenarios with $\mu > 0$ (a), and $\mu < 0$ (b).

under contract HPRN-CT-2002-00292; and the Academy of Finland.

[1] P.W. Higgs, Phys. Lett. **12**, 132 (1964), Phys. Rev. Lett. **13**, 508 (1964), Phys. Rev. **145**, 1156 (1966).
[2] S. Dawson, A. Djouadi, and M. Spira, Phys. Rev. Lett. **77**, 16 (1996).
[3] F. Maltoni, Z.Sullivan, and S. Willenbrock, Phys. Rev. **D67**, 093005 (2003).
[4] R.V. Harlander, W.B. Kilgore, Phys. Rev. **D68**, 013001 (2003).
[5] ALEPH, DELPHI, L3, and OPAL Collaborations, LHWG-Note 2004-01 (2004).
[6] DØ Collaboration, DØNote 5503-CONF (2006).
[7] CDF Collaboration, CDF Note 9854 (2007).
[8] A. Abulencia et al. *et al.* (CDF collaboration), Phys. Rev. Lett. **96**, 011802 (2006).
[9] V. Abazov *et al.* (DØ Collaboration), Phys. Rev. Lett. **97**, 121802 (2006).
[10] CDF Collaboration, CDF Note 5331 (2007).
[11] S. Klimenko, J. Konigsberg, and T.M. Liss, FERMILAB-FN-0741 (2003).
[12] D. Acosta *et al.*, Phys. Rev. **D71**, 032001 (2005).
[13] A. Anastassov *et al.*, Nucl. Instrum. and Methods **A518**, 609 (2004).
[14] T. Sjöstrand *et al.*, Comput. Phys. Commun. **135**, 238 (2001). We use PYTHIA v. 6.215.
[15] H.L. Lai *et al.* (CTEQ Collaboration), Eur. Phys. J. C **12**, 375 (2000).
[16] Z. Was *et al.*, Nucl. Phys. Proc. Suppl. **98**, 96 (2001).
[17] R. Brun and F. Carminati, CERN Programming Library Long Writeup **W5013** (1993).
[18] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. Lett. **94**, 091803 (2005).
[19] A. Bhatti *et al.*, Nucl.Instrum.Meth. **A566**, 375 (2006).
[20] M. Carena, S. Heinemeyer, G. Weiglein, and C.E.M. Wagner, Eur.Phys.J. **C45**, 797 (2006).
[21] M. Spira, Nucl. Instrum. Meth. **A389**, 357 (1997).
[22] S. Heinemeyer, W. Hollik, and G. Weiglein, Eur. Phys. J. C **9**, 343 (1999); Comput. Phys. Commun. **124**, 76 (2000).
[23] M. Carena, S. Heinemeyer, C.E.M. Wagner, and G. Weiglein, hep-ph/9912223 (1999); Eur. Phys. J. C **26**, 601 (2003).